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Establishing Measurement Uncertainty for the Digital Temperature Scanner Using Calibration Data

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14. ABSTRACT

This report documents a methodology to compute the measurement uncertainty for a family of digital temperature scanners using as-found calibration data. Two methods for analyzing the DC voltage measurement calibration errors are described: (1) a lumped method which pools all errors into a single population without regard to input voltage level and (2) a grouped method which separates errors according to the input voltage level. The lumped method has the advantage of establishing a single measurement uncertainty for measurements made at any input level. The disadvantage is that the measurement uncertainty is valid only near midscale because of gain errors that bias the uncertainty calculations. The grouped method's advantage overcomes the disadvantages of the lumped method by presenting measurement uncertainty as a percent of reading format. The disadvantage is additional complexity in computing measurement uncertainty as a function of input voltage level.

15. Subject Terms

Measurement uncertainty, calibration errors, calibration intervals, digital temperature scanners, thermocouple measurement systems

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1.0 INTRODUCTION

1.1 BACKGROUND

AEDC's thermocouple measurement systems consist of multi-channel standalone uniform temperature references (UTRs) and direct current (DC) voltage measurement systems. The UTR converts from thermocouple wire to copper wire and provides an accurate measurement of the temperature at that junction. The DC voltage measurement equipment digitizes the thermocouple voltage output using an analog-to-digital converter (ADC). Separate processing is provided to convert the digitized voltages to temperature in °C.

The existing thermocouple measurement systems are obsolete and are being replaced with multi-channel digital temperature scanners (DTS). Each DTS is configured as a 16-, 32-, or 64-channel system. Each DTS includes a UTR, a DC voltage measurement ADC, and engineering unit processing within the unit. These modular units are capable of being located in environments ranging from -5 to 60°C without requiring environmental protection. This enables the DTS to be located in the test cell close to the engine, thus reducing test buildup and installation time.

1.2 PURPOSE

The purpose of this report is to document the DTS measurement uncertainty using data that are a byproduct of the routine periodic calibration process. The calibration process replaces the input thermocouples with a known National Institute of Standards and Technology (NIST) traceable DC voltage standard. The difference between measured voltage and applied voltage is defined as error (Ref. 1). This calibration process is repeated for each thermocouple channel at eight different voltages and the calibration results are used to statistically quantify the performance of either a single DTS or a family of DTS using measurement uncertainty concepts (Refs. 2-4). These data, which are collected before any adjustments are made to the DTS, are referred to as "as-found" or "as-received" data. This terminology distinguishes such data from data collected after adjustment, which are referred to as "as-left" or "as-returned" data.

2.0 STATEMENT OF THE PROBLEM, APPROACH, AND METHOD OF ANALYSIS

2.1 PROBLEM STATEMENT

Thermocouples are differential temperature measuring instruments. As such, the voltage produced by the thermocouple circuit is a function of the temperature difference between the thermocouple's hot (i.e., measuring) junction and the cold (i.e., reference) junction. Because thermocouples are differential measuring instruments, the problem in constructing the DTS measurement uncertainty is that both the reference junction temperature and the thermocouple analog voltage must be precisely known and their individual uncertainties combined to establish the overall DTS measurement uncertainty.

To accommodate AEDC's dual use of the DTS as both a thermocouple measurement system and a low-level DC voltage measurement system, the measurement uncertainty must be developed in two ways. For thermocouples, the measurement uncertainty must include the accuracy of the reference junction as well as the accuracy of the DC voltage measurement. For low-level DC volt measurement applications, the reference junction temperature is not used since the measurements are voltages and not thermocouples. In this case, the measurement uncertainty would exclude the reference junction

2.2 APPROACH

The approach is to use as-found calibration data to determine measurement uncertainty. The collecting of as-found calibration data is detailed in AEDC's locally developed calibration procedure, LDP-AEDC-34. The procedure separates the calibration into the DC voltage element and the reference junction element. The tolerance for the analog channels is ±16µV, which corresponds to ±0.4°C using an average thermocouple sensitivity of 0.041mV/°C. This DC voltage tolerance was developed from the manufacturer's overall accuracy specification of ±0.5°C by allocating ±0.4°C to DC voltage and ±0.3°C to the reference junction. Each DTS channel is calibrated individually by applying known DC voltages in eight steps ranging from -5mV to 65 mV. At each input the error is determined. This provides eight measures of error for each DTS channel.

The approach to document the reference junction uncertainty used calibrated thermocouples as inputs. For each 16-channel reference block, two thermocouples immersed in an electronic ice bath were input to the DTS. This process was repeated at three environmental temperatures: 60°C; ambient, which is nominally 22°C; and -5°C. The ice bath data from the thermocouples were used to determine the measurement uncertainty of the reference junction.

2.3 METHOD OF ANALYSIS

The DTS is a stand-alone thermocouple measurement system. The system provides for accurate measurement of DC voltages and for accurate measurement of the uniform temperature reference. The latest DC voltage calibration from each DTS was analyzed to quantify the uncertainty of the voltage measurement. Additionally, calibration data documenting the DTS performance at -5, 22, and 60°C were analyzed to quantify the performance over the operating temperature range. These data were combined using RSS to establish the measurement uncertainty.

3.0 RESULTS

3.1 DC VOLTAGE MEASUREMENT ERRORS

3.1.1 Analyzing Errors for Each DTS Unit

The latest DTS DC voltage calibrations from 2012 or 2013 were used to quantify the DC voltage errors. The as-found or as-received calibration data from 46 individual units were analyzed. The data were used to establish the measurement uncertainty for each unit. The data were also pooled together and used to create the measurement uncertainty for the family.

Table 1 is a list of the individual statistics for each of the 46 DTS units. Each unit's statistics (average, standard deviation and standard uncertainty) are computed from the as-found calibration errors and presented as mV errors.

Table 1. Individual DTS DC Volt Statistics

DTS	AVG, mV	SIGMA, mV	uc, mV	DTS	AVG, mV	SIGMA, mV	uc, mV
F230774	-0.001	0.011	0.011	F242783	0.003	0.004	0.005
F230775	-0.001	0.003	0.003	F242800	-0.001	0.003	0.003
F230776	0.001	0.003	0.004	M014548	0.003	0.004	0.005
F230777	0.001	0.004	0.004	M014549	0.007	0.006	0.009
F235082	0.001	0.005	0.005	M014550	0.001	0.004	0.004
F239546	-0.001	0.004	0.004	M014551	-0.001	0.004	0.004
F239547	0.001	0.004	0.005	M014552	0.006	0.007	0.009
F239548	0.005	0.006	0.008	M014553	0.002	0.004	0.004
F239549	0.001	0.004	0.004	M014554	0.002	0.004	0.004
F239550	0.003	0.006	0.007	M014555	0.003	0.004	0.005
F239555	0.002	0.004	0.005	M014844	-0.001	0.003	0.003
F239557	0.006	0.006	0.009	M014845	0.010	0.009	0.013
F239560	0.002	0.005	0.005	M015226	0.007	0.006	0.009
F239561	0.002	0.005	0.005	M015227	0.006	0.005	0.008
F239563	0.005	0.006	0.008	M015228	0.003	0.004	0.005
F239564	0.004	0.005	0.006	M015230	0.002	0.004	0.005
F239572	0.001	0.004	0.004	M015231	0.003	0.005	0.006
F239573	0.001	0.004	0.004	M015232	0.005	0.005	0.008
F239739	0.000	0.002	0.002	M015233	0.001	0.002	0.002
F239740	0.004	0.004	0.006	M015234	0.007	0.007	0.010
F242741	0.000	0.004	0.004	M015235	0.006	0.007	0.009
F242777	0.002	0.004	0.004	M015236	0.005	0.007	0.008
F242778	-0.001	0.003	0.003	M016055	0.005	0.006	0.007

3.1.2 Analyzing Errors at Each Input Voltage Level

Table 2 lists the DTS unit statistics at each input voltage: -5, 0, 6, 18, 30, 42, 54, 65 mV. The statistics were computed for each input voltage level by pooling all channels from all 46 DTS units. At each input voltage level, there are 1,884 individual errors.

Figure 1 illustrates the U_{95} measurement uncertainty as a function of input voltage level for both the as-left and as-received calibration data. The as-left uncertainty is relatively constant across the input voltage levels. In contrast, the as-received data indicate a bias error across all input voltages coupled with a gain error at inputs greater than 18 mV.

Table 2. DTS DC Volt Measurement Statistics

	-5 mV	0 mV	6 mV	18 mV	30 mV	42 mV	54 mV	65 mV
AVG, mV	0.000	-0.001	0.001	0.002	0.003	0.004	0.005	0.006
SIGMA, mV	0.004	0.004	0.004	0.004	0.005	0.006	0.006	0.007
uc, mV	0.004	0.004	0.004	0.005	0.006	0.007	0.008	0.009
U95, mV	0.008	0.008	0.008	0.009	0.011	0.013	0.016	0.018

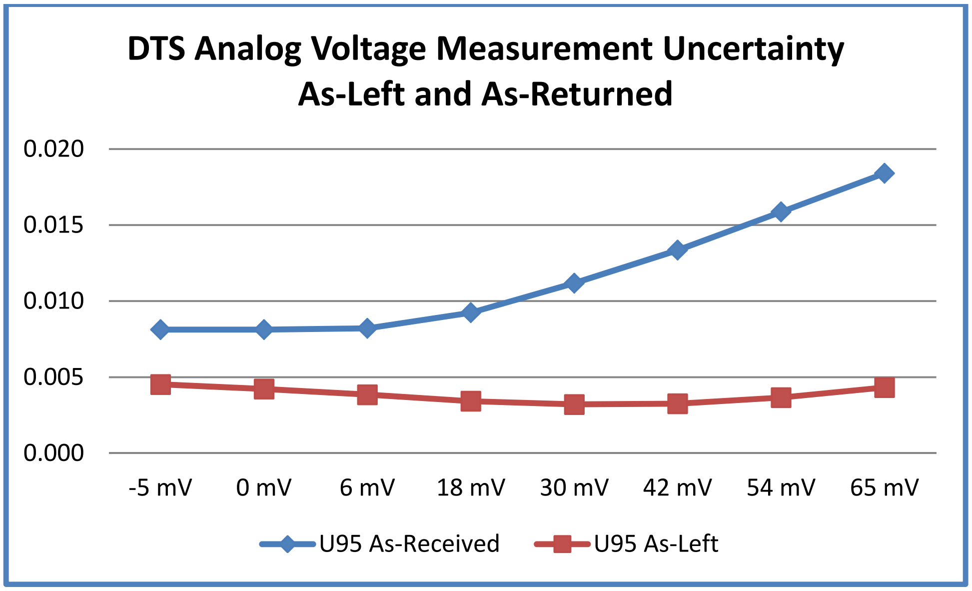

Figure 1. Analog Voltage Measurement Uncertainty at Each Input Voltage Level

3.1.3 Analyzing Errors for the Population of DTS Units

The errors from all 46 DTS units were combined to establish the distribution of errors. This distribution is shown in Fig. 2. The statistics for this population are as follows:

- Average Error: 0.002 mV
- Standard Deviation: 0.006 mV
- Standard Uncertainty: 0.006 mV
- Expanded Uncertainty, U_{95} : ±0.012 mV

The expanded uncertainty (U95 = ±0.012 mV) obtained by lumping all errors together corresponds to the uncertainty at the 30- to 42-mV level (refer to Table 2). Thus, the pooled approach provides an averaged value of uncertainty across all input voltages. Accordingly, the pooled approach may not be acceptable if the measurements are greater than 42 mV since the pooled approach understates the measurement uncertainty (refer to Table 2).

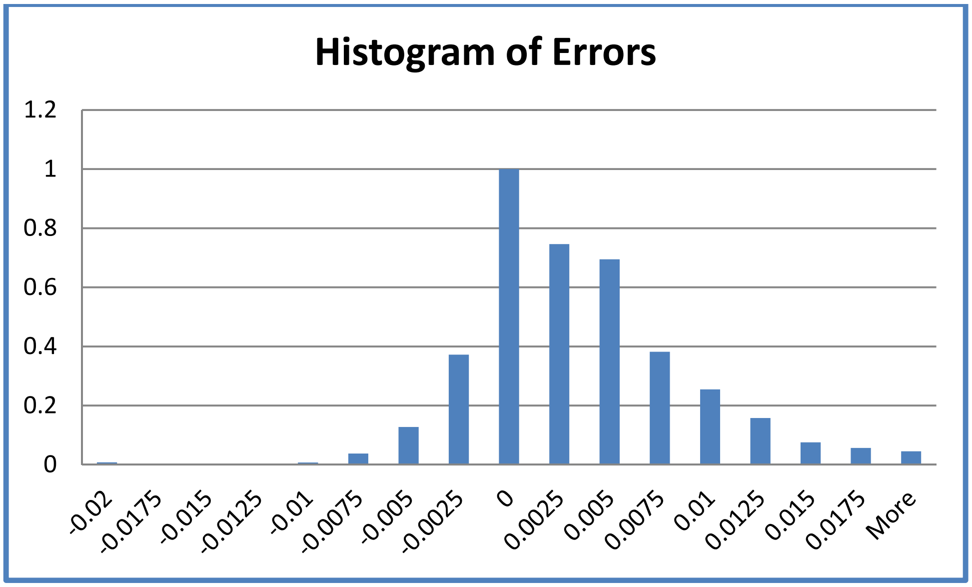

Figure 2. Distribution of Errors for Analog Voltage Measurement

3.2 UNIFORM TEMPERATURE REFERENCE JUNCTION

The DTS utilizes an isothermal UTR for each 16-channel block of inputs. Two precision 100-ohm RTDs located at the ends of the block are used to measure each reference junction block. These are then averaged to provide the reference temperature for the block.

The uncertainty of the UTR is not measured directly; rather, it is indirectly determined. Two reference thermocouples are used as inputs for each isothermal block. The thermocouples are immersed in an ice bath and connected to the first and last channels of each block (e.g., channels 1 and 16, channels 17 and 32, etc.). The analog outputs of these channels are measured and errors determined as the difference between the ice bath thermocouples (nominally zero mV) and the analog voltage. As a result, the measurement error represents the total error of the reference thermocouple immersed in an ice bath, the UTR accuracy as measured by reference RTDs, and the analog voltage measurement error for that channel.

AEDC's approach was to obtain calibration data using ice point reference thermocouples at -5, 22, and 60°C. No attempt was made to isolate the UTR accuracy from the calibration data.

Figure 3 illustrates the error histograms for the ice bath thermocouples at three ambient temperatures. The data were collected by inserting the DTS in an environmental chamber and setting the temperature to -5, 22, and 60°C. The units were allowed to stabilize at each temperature and data collected from the ice bath thermocouples.

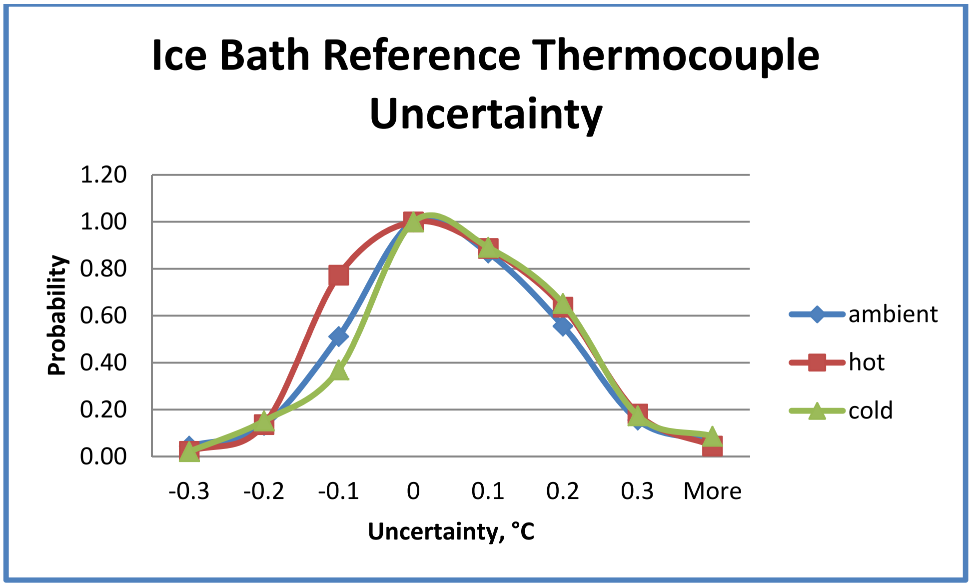

Figure 3. Ice Bath Thermocouple Measurement Uncertainty at Different Ambient Temperatures

Table 3 documents the parameters for each of the three temperatures. As shown, the expanded uncertainty which includes the reference junction and the analog voltage uncertainty is less than 0.3°C and is well within the total specification of 0.5°C.

The reference junction uncertainty can be determined using the as-left analog voltage uncertainty and the ice bath thermocouple uncertainty. The as-left analog uncertainty data at the 0-mV input voltage level (see Fig. 1) is 0.0043 mV and corresponds to 0.1°C. Using this and the ice bath reference thermocouple uncertainty of 0.27°C, the reference junction uncertainty is determined from RSS to be 0.25°C.

Table 3. Ice Bath Reference Thermocouple Uncertainty

Parameter	**-5**°C	**22**°C	**60**°C
Sample Size	154	150	162
Average, °C	0.018	0.005	-0.004
Standard Deviation, °C	0.134	0.134	0.133
Standard Uncertainty, °C	0.135	0.134	0.133
Expanded U95 Uncertainty, °C	0.271	0.268	0.266

3.3 COMBINED UNCERTAINTY

The measurement uncertainty includes the DC voltage measurement errors, UTR error, UTR gradient, NIST interpolating polynomial error, and calibration standards. The elemental errors are presented in Table 4. These elemental errors are combined using RSS to provide an expanded uncertainty of ±0.44°C, which is consistent with the specification of ±0.5°C.

The standard uncertainty in Table 4 represents the standard uncertainty of the population of all DTS voltage measurement errors. Since the uncertainty increases with gain (see Fig. 1 or Table 2), the pooled value is biased and is only representative of the uncertainty near the 30mV input voltage level. For voltage measurements less than 30 mV, the pooled value overstates the DTS measurement uncertainty. Similarly, for measurements greater than 30 mV, the pooled value understates the DTS measurement uncertainty. Accordingly, it may be preferable to use the measurement uncertainty corresponding to the particular input voltage of interest rather than to use the pooled method.

Table 4. Components of DTS Measurement Uncertainty

Standard Uncertainty Component, °C	Value, °C	Comments
DC Voltage Measurement	0.15	Corresponds to standard uncertainty of 0.006 mV (Section 3.1.3)
UTR Accuracy	0.13	Table 3
UTR Gradient	0.05	Estimated based on Scanivalve data
Interpolating Polynomial	0.05	NIST ITS-90 Polynomials
Standards	0.06	Fluke 5440B, Kaye 140
Combined Standard Uncertainty	0.22	
Expanded Uncertainty, U95	0.44	

3.3.1 DTS Measurement Uncertainty for ANSI Type Thermocouples

The average sensitivities for thermocouples most often used at AEDC are presented in Table 5. The uncertainty for each thermocouple type is illustrated in Figs. 4-7.

Table 5. Thermocouple Average Sensitivity

ANSI Type Thermocouple	Average Sensitivity, mV/°C
Type K	0.041
Type J	0.055
Type T	0.043
Type E	0.068

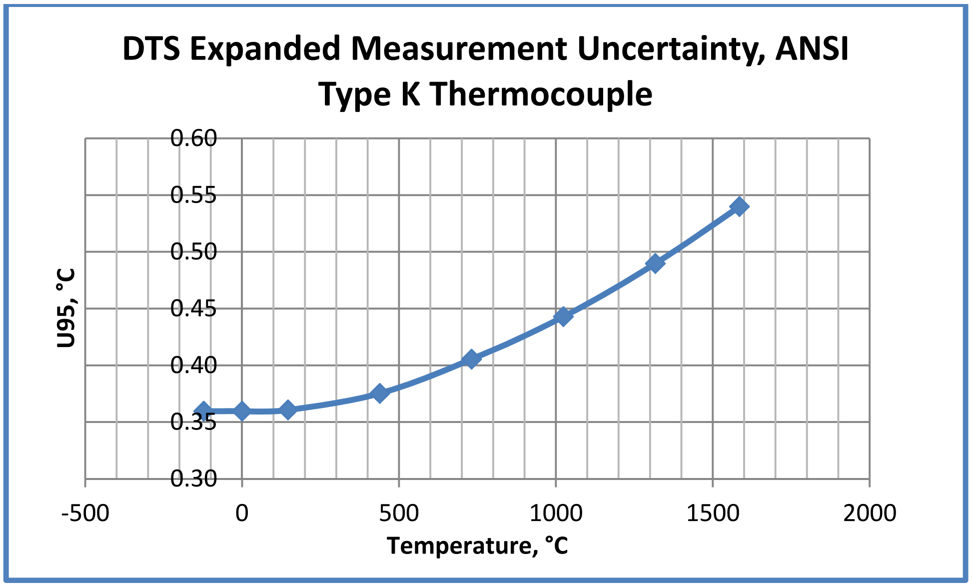

Figure 4. Measurement Uncertainty for ANSI Type K Thermocouple

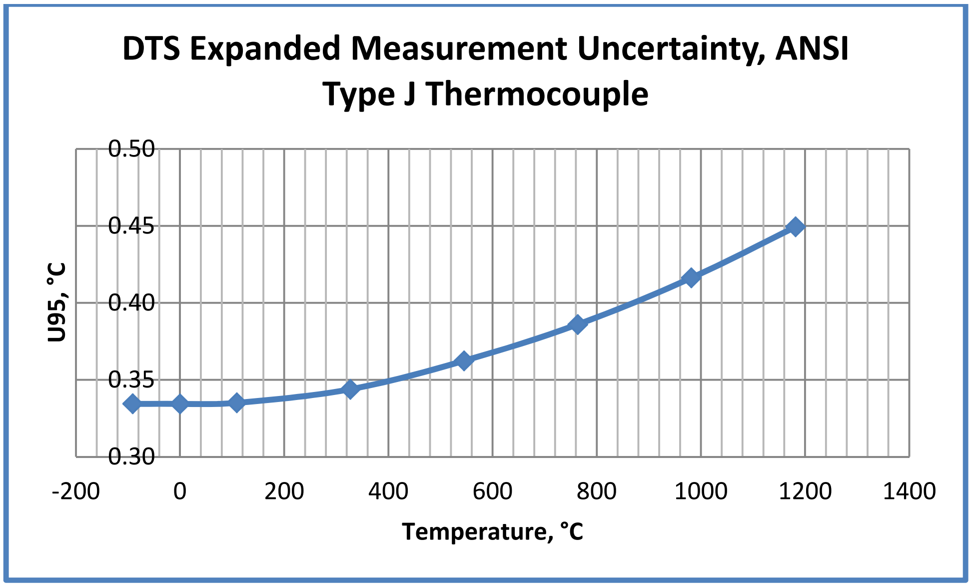

Figure 5. Measurement Uncertainty for ANSI Type J Thermocouple

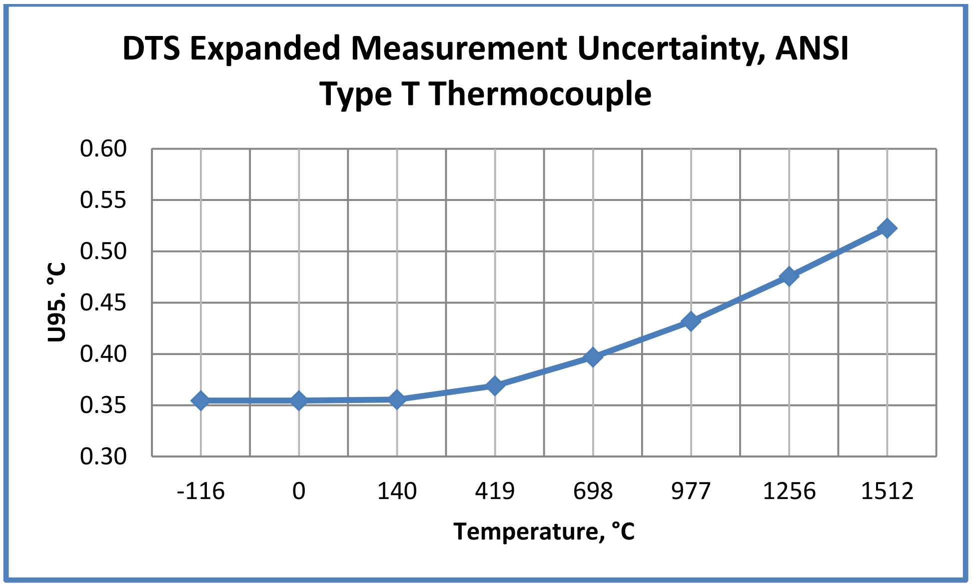

Figure 6. Measurement Uncertainty for ANSI Type T Thermocouple

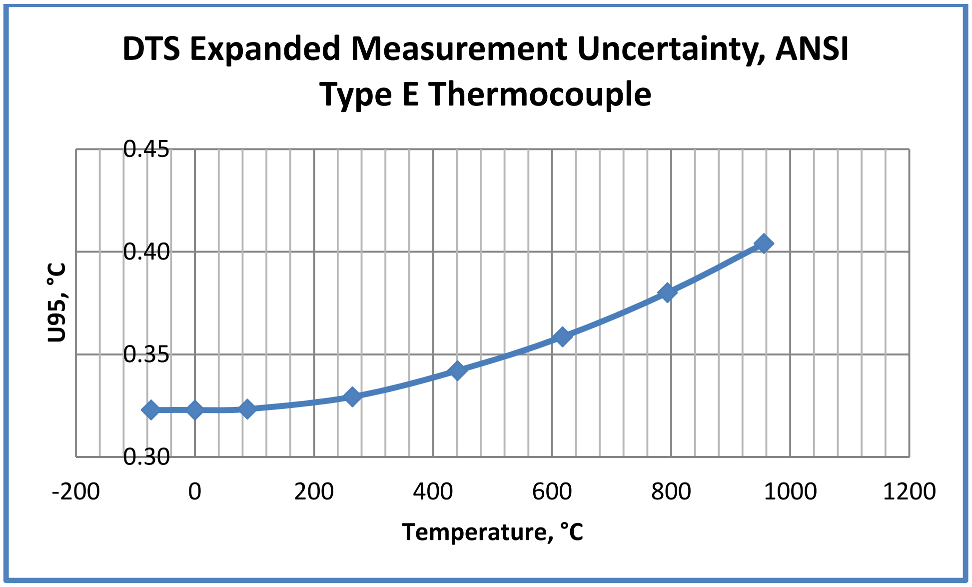

Figure 7. Measurement Uncertainty for ANSI Type E Thermocouple

4.0 SUMMARY

As-found calibration data from 46 individual DTS were analyzed and used to establish the measurement uncertainty for the DTS family. The calibration data consisted of (1) as-found calibration errors for each channel at eight different voltage levels established by applying known DC voltages into each channel and (2) reference junction calibration errors at nominally -5, 22, and 60°C environmental temperatures. The reference junction errors were established using calibrated thermocouples that were immersed in an ice bath.

For the DC voltage calibrations, two different approaches were used to analyze the calibration data. First, the uncertainty analysis was performed for the DTS family by pooling their calibration errors together and using descriptive statistics to establish population statistics. Second, the analysis was performed at each of the eight input voltage levels by combining all 46 DTS at that voltage level. At each input voltage level, descriptive statistics were used to establish the standard uncertainty. Both methods provide comparable results. However, the second method which provides measurement uncertainty at each input level offers the advantage of using percent of reading and may be advantageous to the analyst.

The reference junction errors were analyzed by pooling all errors at each of the three environmental temperatures. The statistics for the environmental temperatures were consistent.

In summary, the DTS measurement uncertainty was determined to be within the manufacturer's specification of $U_{95} = \pm 0.5°C$. If the analyst requires a single value for uncertainty, then $U_{95} = \pm 0.5°C$ should be quoted. Because there is an observed percent of reading trend with the analog voltage measurement uncertainty, there are advantages to quoting uncertainty in terms of percent reading that the analyst should consider.

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NOMENCLATURE

AEDC	Arnold Engineering Development Complex
ADC	Analog to digital converter
DTS	Digital temperature scanner
FS	Full scale
NIST	National Institute of Standards and Technology
RTD	Resistance temperature detector
RSS	Root sum square
UTR	Uniform temperature reference
U_C	Standard uncertainty
U_{95}	95% confidence interval for measurement uncertainty